Applied Energy 112 (2013) 1161–1165

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A flameless catalytic combustion-based thermoelectric generator for powering electronic instruments on gas pipelines

Heng Xiao [a,b,*], Kuanrong Qiu [b], Xiaolong Gou [a,*], Qiang Ou [a]

[a] School of Power Engineering, Chongqing University, Chongqing 400044, PR China
[b] CanmetENERGY – Ottawa, Natural Resources Canada, 1 Haanel Drive, Ottawa, Ontario, Canada K1A 1M1

HIGHLIGHTS

- ▶ MPPT is used to improve the feature that TEG output is sensitive to load variation.
- ▶ The improved feature makes TEG suitable to power electronic device on gas pipeline.
- ▶ Test shows heat transfer uniformity plays an important role in improving TEG output.
- ▶ It can get an optimized TEG by uniformly filling a thermal insulation material.

ARTICLE INFO

Article history:
Received 17 September 2012
Received in revised form 10 December 2012
Accepted 26 January 2013
Available online 22 February 2013

Keywords:
Thermoelectric generator
Flameless catalytic combustion
Gas pipeline
Maximum power point tracking
Combustion chamber

ABSTRACT

This paper presents a flameless catalytic combustion-based thermoelectric power generator that uses commercial thermoelectric modules. The structure of the thermoelectric generator (TEG) is introduced and the power performance is measured based on a designed circuit system. The open circuit voltage of the TEG is about 7.3 V. The maximum power output can reach up to 6.5 W when the load resistance matches the TEG internal resistance. However, the system output is sensitive to load variation. To improve this characteristic, maximum power point tracking technique is used and results in an open circuit voltage of 13.8 V. The improved characteristic makes the TEG system a good charger to keep the lead acid battery fully charged so as to meet the needs of electronic instruments on gas pipelines. In addition, the combustion features have been investigated based on the temperature measurement. Test results show that the uniformity of combustion heat transfer process and the combustion chamber structure play important roles in improving system power output. It can get an optimized TEG system (maximum power output: 8.3 W) by uniformly filling a thermal insulation material (asbestos) to avoid a non-uniform combustion heat transfer process.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Thermoelectric generator (TEG) has no moving parts, and is compact, quiet, highly reliable, and environmentally friendly. However, applications of thermoelectric (TE) power generation have been limited because of relatively low heat-to-electricity conversion efficiency.

Since waste heat is a low-cost and even no-cost resource, the low efficiency of TE devices may not be the most important issue in the case. It has been shown that the TE power generation applied to low-temperature waste heat recovery has promising potential [1–6].

Meanwhile, for some applications, it is necessary to adopt a high-temperature heat source to improve system performance. Fuel burning seems a good way to achieve this target and has been utilized in many applications. Qiu and Hayden [7] presented a combustion-driven thermoelectric power generation system that uses PbSnTe-based thermoelectric modules which were integrated into a gas-fired furnace with a special burner design. The thermoelectric integrated system could be applied for self-powered appliances or micro-cogeneration. Champier et al. [8] investigated the feasibility of adding commercial TE modules (Bismuth Telluride) to the biomass cook stove prototype to search the best position of the modules. A TE power generator experimental set up was presented showing that a 6 W ready to use electrical production is possible with the biomass cook stove. Jiang et al. [9] developed a centimeter magnitude TE power generation system based on a

* Corresponding authors Address: School of Power Engineering, Chongqing University, Chongqing 400044, PR China. Tel.: +86 23 65103512; fax: +86 23 65102473.

E-mail addresses: xh-840822@163.com (H. Xiao), kqiu@nrcan.gc.ca (K. Qiu), simgxl@cqu.edu.cn (X. Gou), julianoq@163.com (Q. Ou).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.01.078

plat-flame micro combustor burning DME (dimethyl ether). The maximum power output was above 2 W, and the maximum overall chemical-electric energy conversion efficiency was 1.25%.

It seems that combustion is an effective method, in a wide range of temperature, to produce thermal energy which to be used by thermoelectric generator. However, the system efficiency is still so low that the more electricity the TEG generates, the more heat it losses.

Nowadays, some researchers proposed an idea that integration of TEG with conventional thermal equipment, thus, to improve the overall system efficiency. Chen et al. [10] presented an analysis of system efficiency related to the integration of TEG into thermal energy systems, especially Combined Heat and Power production (CHP). The overall conversion efficiency improvements and economic benefits, together with the environmental impact of this deployment, were estimated. Moreover, Qiu and Hayden [11] developed the concept of cascading TPV and TE power generation where the used heat stream is taken from the TPV and applied to the input of a TE converter. Experimental results show that the cascading power generation is feasible in fuel-fired heating furnaces and could be applied to micro-CHP.

This paper will discuss a power solution for electronic instruments on gas pipelines. These electronic devices, used only for pipeline cathodic protection, monitoring and communication, have a very small demand for electricity. It is unstable and uneconomic to offer a power grid for these remote devices. As mentioned above, thermoelectric generator is very suitable to be installed in the field to power electronic instruments on gas pipelines, just by burning a very small amount of natural gas for heat. In particular, the photovoltaic system provides electrical power during sunshine, while the TE system provides power as long as the heating device is in use.

However, fossil fuel combustion causes air pollution and greenhouse gas emissions. In order to alleviate this problem, flameless catalytic combustion technology of natural gas is employed in this study. On the one hand, natural gas is a relatively clean fuel. On the other hand, flameless catalytic combustion can lower the combustion temperature so as to reduce the generation of nitrogen oxides. Badra and Masri [12] recently studied catalytic combustion of selected hydrocarbon fuels on platinum. And many application examples were carried out [13], especially employing methane [14], alcohols [15] as fuels.

For the integration of TEG with flameless catalytic combustion, Wang et al. [16] designed and simulated a micro-thermoelectric-generator based on catalytic combustion of hydrogen and oxygen. The effect of inlet parameters on the highest temperature difference between the hot and cold plate of the generator was studied. Federici et al. [17] studied integrated catalytic micro-combustors with thermoelectric devices for the production of electrical power. The devices were found to be robust, easy to start up, and able to support complete combustion over a range of fuels at different flow-rates. Yoshida et al. [18] developed a miniature TEG with a catalytic combustor for applications where exhaust heat is useful. The characteristics of TE generation were measured using hydrogen as fuel. When a theoretical combustion power was 6.6 W, the maximum output power of 184 mW was obtained.

However, the power capacity of such TE devices is so small that it cannot be used as an on-site power supply to meet the needs of electronic instruments on gas pipelines. In such an application where a lead acid battery is used to provide high peak power for short burst requirements (such as for wireless communications at remote monitoring sites), a thermoelectric generator which can produce a 12 or 24 V power source to keep the battery fully charged is needed.

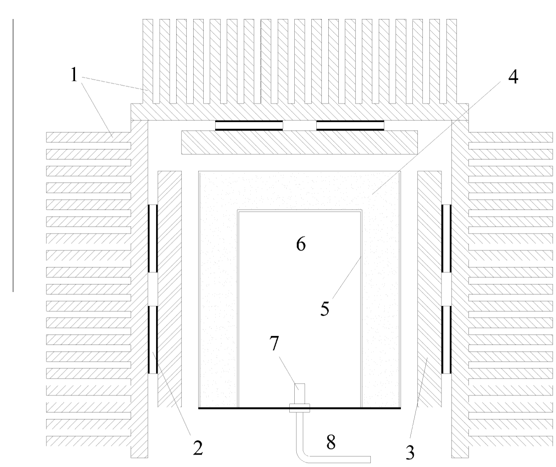
This paper presents a flameless catalytic combustion-based TEG that uses commercial TE modules and with a bigger combustion chamber size to enhance the system power output so as to meet the needs of electronic instruments on gas pipelines. The structure of the TEG is introduced and the power performance is measured based on a designed circuit system. The combustion aspects are also investigated. Several different characteristics from conventional combustion heat utilization of flameless catalytic combustion are discussed.

2. Experimental setup

Fig. 1 is the schematic diagram of the flameless catalytic combustion-based TEG (top view). In this study, a rectangular combustion chamber is set as the heat source of the TEG. In order to establish an appropriate temperature difference, this chamber is surrounded by three large heat sinks on which the cold sides of the TE modules are fixed. The front side of the chamber, i.e. the inlet of natural gas, is not covered by TE modules and heat sink.

To fix the TE modules tightly on the base surface of the heat sink, a thermal plate is attached to the hot sides of the modules on each heat sink. Thus, the TE modules are sandwiched between the heat sink and thermal plate by bolts. Moreover, the utilization of thermal plates could protect the TE modules from high temperature corrosion and make the heat transfer process across the modules uniform. It should be noted that, to prevent the modules from high temperatures damage and make the cold sides of these modules to be well cooled, the TE modules are not placed in the combustion chamber. The TE modules just take advantage of the natural gas combustion heat out of the combustion chamber (indirect use of the combustion heat). This is totally different from conventional combustion heat utilization of flameless catalytic combustion, where the heat transfer equipment is directly arranged in the combustion chamber.

Since the hot side temperature of the modules is calculated to be lower than 200 °C, the thermoelectric module for cooling, which is cheap and can achieve its highest efficiency at room temperature, is selected in this study. Four commercial TE cooling modules (Model: TEC1-12708, Dimension: 40 mm × 40 mm × 3.5 mm) are configured on each heat sink. These four modules are connected electrically in series. Both surfaces of each TE module are coated with thermal grease to enhance heat conduction. Fig. 2 shows the internal structure of the TEG without the combustion chamber.



1-Heat sink 2-Thermoelectric module 3-Thermal plate 4-Asbestos layer
5-Porous metal plate (catalytic reaction layer) 6-Combustion chamber
7-Nozzle 8-Natural gas tube

Fig. 1. Schematic diagram of the flameless combustion-based TEG (top view).

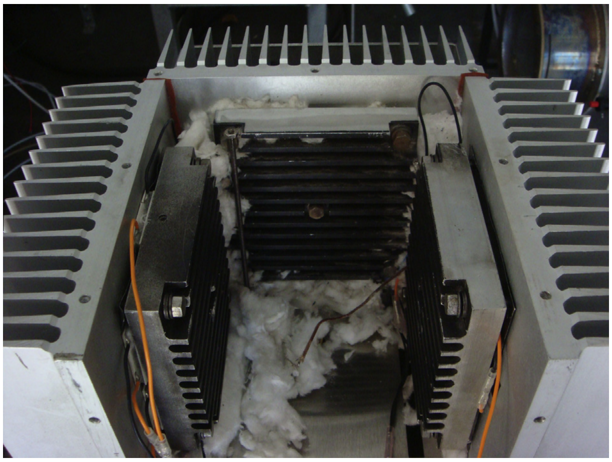


Fig. 2. Internal structure of the TEG.

The combustion chamber wall is made by a porous metal plate coated with alumina-supported 0.2 wt.% platinum catalyst, where the catalytic combustion of natural gas occurs. A thick layer of asbestos is adopted to surround the flameless catalytic combustion chamber, in order to ensure even and stable combustion and to reduce heat loss. Fig. 3 shows the internal structure of the combustion chamber with asbestos layer.

In this investigation, two thermocouples are embedded into the left- and right-side thermal plates (as shown in Figs. 1 and 2) respectively for temperature measurement. As mentioned above, there are three groups of TE modules that are configured on the left, right and back heat sinks, respectively. These three groups of modules are connected electrically in parallel (each group consists of four modules which are connected electrically in series), and then connected to a variable resistor as a load to form a power circuit. Consequently, the power performance of the TEG can be measured based on this circuit system.

3. Results and discussion

3.1. Power output and conditioning

The start-up of this system is simple, just heating the catalyst by a back-up battery which will be fully charged when the TEG works. The TEG output is recorded and shown in Figs. 4–6 when the system is stable. The open circuit voltage is 7.32 V. As shown in Fig. 6,

Fig. 3. Internal structure of the combustion chamber.

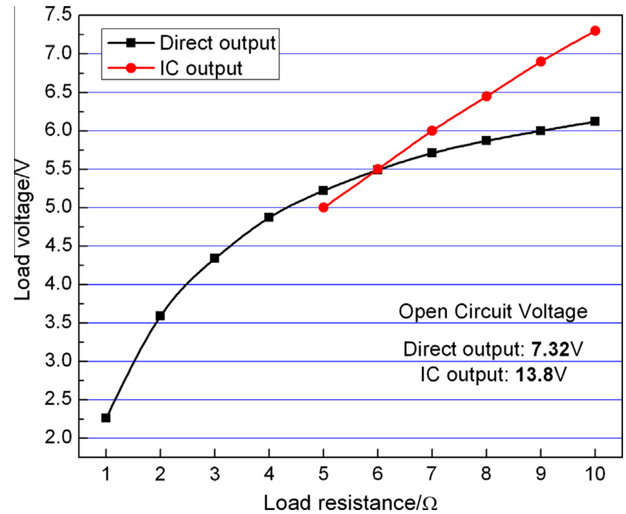


Fig. 4. Load voltage versus load resistance for direct and IC output.

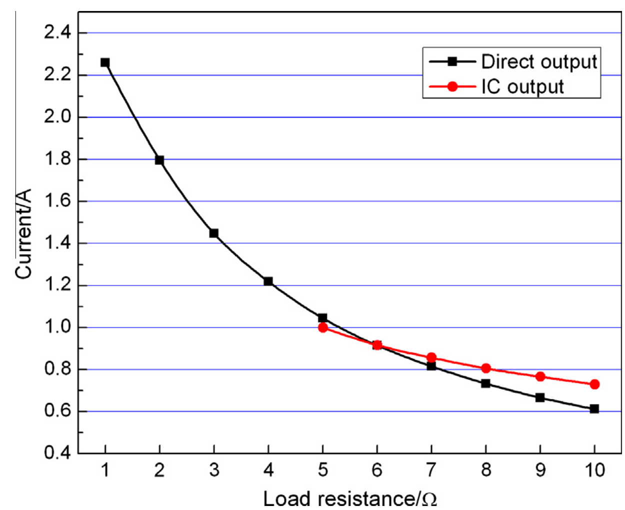


Fig. 5. Current versus load resistance for direct and IC output.

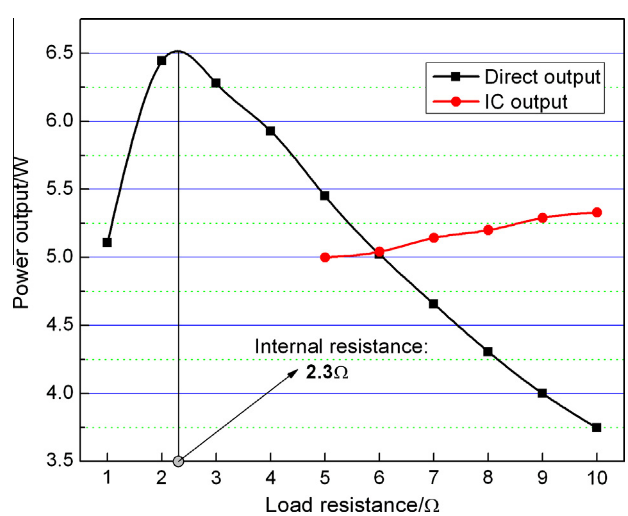


Fig. 6. Power output versus load resistance for direct and IC output.

the maximum power output (about 6.5 W) is generated when the load resistance matches the TEG internal resistance. The fuel

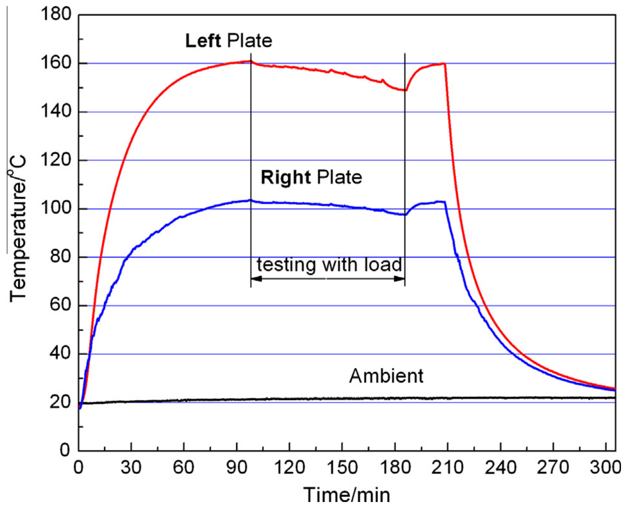


Fig. 7. Temperatures of the left and right thermal plates versus time.

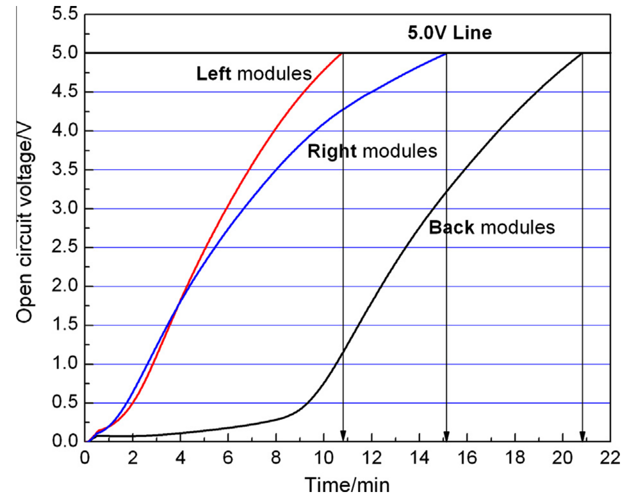


Fig. 8. Open circuit voltages versus time for the three groups of TE modules at the start-up stage.

(natural gas) consumption of this system is 1 m^3/day and the overall efficiency is about 2%. Considering the TE modules utilize combustion heat indirectly and the system only works when the lead acid battery power is low, this efficiency is acceptable.

As shown in Figs. 4–6, the power output is sensitive to load variation. This characteristic would reduce the range of applications and decrease the system efficiency. A solution to this problem is the utilization of maximum power point tracking (MPPT) technique. The MPPT is a well-known control technique which can enable the photovoltaic power system to operate at its maximum power capability under various sunlight intensities. Very recently, this control technique has been introduced into the TEG system [19,20]. In this study, the MPPT controller will utilize the TEG terminal voltage and current to maximize the power output.

The TEG output through MPPT conditioning is recorded and also shown in Figs. 4–6 for comparison. As shown in Fig. 6, the system power output is stabilized at around 5 W. Apparently, the load matching ability has been improved. Introducing MPPT power conditioner do has a potential to reduce mismatch power loss and improve load matching ability of TEG systems. Moreover, the open circuit voltage of the MPPT IC reaches 13.8 V, which is suitable to keep the lead acid battery fully charged so as to meet the needs of electronic instruments on gas pipelines.

3.2. Combustion analysis and structure optimization

The overall system efficiency of about 2% is achieved. The overall system efficiency refers to the conversion efficiency from chemical energy (natural gas) to electrical energy (generated by TEG). In this calculation, the calorific value of natural gas is set as the denominator, and the TEG power output is set as the numerator.

However, for this low efficiency, there is still room for improvement. As mentioned above, the TE modules just take advantage of the natural gas combustion heat out of the combustion chamber (indirect use of the combustion heat). Although the TEG efficiency is low due to the limitation of the thermoelectric material, the indirect utilization of the combustion heat is the key to improve the system efficiency. As a thermal system, the power output of the TEG is subject to the combustion and heat transfer process. For the purpose of investigating the combustion features to improve system performance, temperature is used as a major parameter to analyze the combustion characteristics.

The temperatures of the left and right thermal plates during the test are recorded and shown in Fig. 7. When the system is stable, the left thermal plate can reach up to 160 °C, but the right one can only reach up to a little more than 100 °C. Flameless catalytic combustion should be a combustion mode with very uniform distribution. Since the chamber structure and the assembly layout are symmetrical, the temperature difference is likely due to the non-uniform filling of the thermal insulation material (asbestos), which would result in a non-uniform heat transfer. As mentioned above, the TE modules are not placed in the combustion chamber. The TE modules just take advantage of the natural gas combustion heat out of the combustion chamber. We should pay more attention to the uniformity of combustion heat transfer process. It is a different characteristic from conventional combustion heat utilization of flameless catalytic combustion.

It is noted that there is a temperature drop during testing when the circuit which is connected with a load is closed (Fig. 7). This is because when the circuit is closed the current through the TEG will result in Peltier effect at both junctions (hot and cold sides) of the TE materials. The Peltier effect at the hot side can cause heat absorption while the effect occurs at the cold side can lead to heat dissipation.

Furthermore, the open circuit voltages for the three groups of TE modules (left, right and back) at the start-up stage are measured and plotted in Fig. 8. These curves show that it takes the left

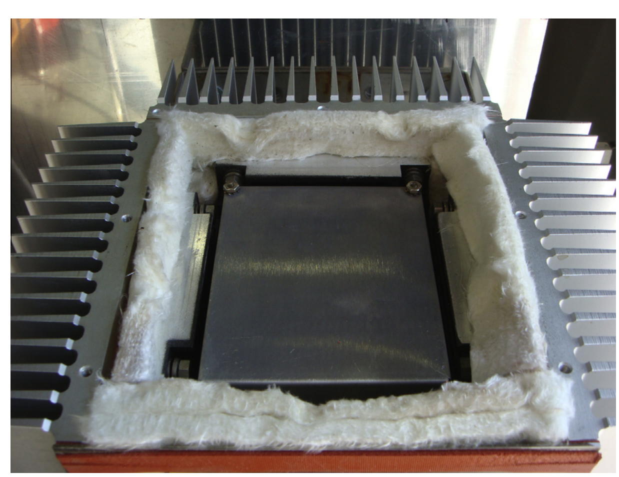


Fig. 9. Internal structure (without roof) of the TEG.

Table 1
Experimental results before and after structural improvement.

	Maximum power output (W)	Power output through MPPT conditioning (W)	Temperature of the left/right thermal plate (°C)
Before structural improvement	6.5	≈5.0	≈155/100
After structural improvement	8.3	≈7.0	≈155/150

modules 11 min to reach 5 V but the right modules about 15 min. For the back modules, of which open circuit voltage do not change significantly at the first 8 min, it takes almost 21 min to cross the 5 V line. These curves illustrate the speed of combustion propagation. There is a relatively long distance between the nozzle and the back-side catalytic media, which leads to the response delay of the back modules. Perhaps we should shorten this distance to accelerate the combustion propagation. It is another different characteristic from conventional combustion heat utilization of flameless catalytic combustion. In further work, we will optimize the arrangement of the porous metal plate (catalytic reaction layer) in order to achieve the maximum overall system efficiency. Actually, exploring how to effectively improve the system efficiency and enhance the system performance is and will be the focus of our work.

Based on the above analysis, an experiment by uniformly filling the thermal insulation material is carried out. The quality homogeneous asbestos is carefully filled to surround the flameless catalytic combustion chamber. In addition, in order to reduce heat loss, some asbestos is adopted to seal the edges of the device. The internal structure (without roof) of the TEG is shown in Fig. 9. The experimental results before and after structural improvement are both listed in Table 1.

The maximum power output can reach up to 8.3 W and the temperature of the right thermal plate is only about 5 °C lower than the left one. The results show that the system performance is improved by uniformly filling the homogeneous thermal insulation material (asbestos). The uniformity of combustion heat transfer process does affect the TEG performance.

4. Conclusion

A flameless catalytic combustion-based TEG has been examined. The open circuit voltage of the TEG is about 7.3 V. The maximum power output can reach up to 6.5 W when the load resistance matches the TEG internal resistance.

It is an efficient method using maximum power point tracking (MPPT) technique to improve the characteristic that the system output is sensitive to load variation and results in an open circuit voltage of 13.8 V. The improved characteristic makes the TEG system a good charger to keep the lead acid battery fully charged so as to meet the needs of electronic instruments on gas pipelines.

In addition, the combustion features have been investigated. Test results show that the uniformity of combustion heat transfer process and the combustion chamber structure play important roles in improving system power output. It can get an optimized TEG system (maximum power output: 8.3 W) by uniformly filling a thermal insulation material (asbestos) to avoid a non-uniform combustion heat transfer process.

Acknowledgement

This work was financed by the NSFC (51276206) and Chinese Government Scholarship.

References

[1] Bell LE. Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. Science 2008;321:1457–61.
[2] Ammar Y, Joyce S, Norman R, Wang YD, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. Appl Energy 2012;89:3–20.
[3] Niu X, Yu JL, Wang SZ. Experimental study on low-temperature waste heat thermoelectric generator. J Power Sources 2009;188:621–6.
[4] Gou XL, Xiao H, Yang SW. Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system. Appl Energy 2010;87:3131–6.
[5] Hsu CT, Huang GY, Chu HS, Yu B, Yao DJ. Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators. Appl Energy 2011;88:1291–7.
[6] Love ND, Szybist JP, Sluder CS. Effect of heat exchanger material and fouling on thermoelectric exhaust heat recovery. Appl Energy 2012;89:322–8.
[7] Qiu K, Hayden ACS. A natural-gas-fired thermoelectric power generation system. J Electron Mater 2009;38:1315–9.
[8] Champier D, Bedecarrats JP, Rivaletto M, Strub F. Thermoelectric power generation from biomass cook stoves. Energy 2010;35:935–42.
[9] Jiang LQ, Zhao DQ, Guo CM, Wang XH. Experimental study of a plat-flame micro combustor burning DME for thermoelectric power generation. Energy Convers Manage 2011;52:596–602.
[10] Chen M, Lund H, Rosendahl LA, Condra TJ. Energy efficiency analysis and impact evaluation of the application of thermoelectric power cycle to today's CHP systems. Appl Energy 2010;87:1231–8.
[11] Qiu K, Hayden ACS. Development of a novel cascading TPV and TE power generation system. Appl Energy 2012;91:304–8.
[12] Badra JA, Masri AR. Catalytic combustion of selected hydrocarbon fuels on platinum: reactivity and hetero-homogeneous interactions. Combust Flame 2012;159:817–31.
[13] Cho ES, Danon B, Jong WD, Roekaerts DJEM. Behavior of a 300 kW_{th} regenerative multi-burner flameless oxidation furnace. Appl Energy 2011;88:4952–9.
[14] Yin J, Su S, Yu XX, Weng YW. Thermodynamic characteristics of a low concentration methane catalytic combustion gas turbine. Appl Energy 2010;87:2102–8.
[15] Behrens DA, Lee IC, Waits CM. Catalytic combustion of alcohols for microburner applications. J Power Sources 2010;195:2008–13.
[16] Wang F, Zhou J, Wang GQ, Zhou XJ. Simulation on thermoelectric device with hydrogen catalytic combustion. Int J Hydrogen Energy 2012;37:884–8.
[17] Federici JA, Norton DG, Bruggemann T, Voit KW, Wetzel ED, Vlachos DG. Catalytic microcombustors with integrated thermoelectric elements for portable power production. J Power Sources 2006;161:1469–78.
[18] Yoshida K, Tanaka S, Tomonari S, Satoh D, Esashi M. High-energy density miniature thermoelectric generator using catalytic combustion. J Microelectromech Sys 2006;15:195–203.
[19] Eakburanawat J, Boonyaroonate I. Development of a thermoelectric battery-charger with microcontroller-based maximum power point tracking technique. Appl Energy 2006;83:687–704.
[20] Yu C, Chau KT. Thermoelectric automotive waste heat energy recovery using maximum power point tracking. Energy Convers Manage 2009;50:1506–12.